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TITLE: DEVELOPMENT OF AN UPSTREAM AIR-START SYSTEM FOR PULSEJET ENGINES

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MODEL NO. CONTRACT NO. AF 33(600) - 15613

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1. SUMMARY

A starting system for pulsejets using the NRL vane-seating type of air inlet valves has been developed that provides positive starts within one or two seconds. The system has been used on AJ-5.0, AJ-6.75, and AJ-7.5-1 pulsejets with the baffled-nozzle fuel system, and on AJ-5.0 and AJ-6.75 pulsejets using the new "upstream" fuel system. Air is injected aft through the valve reeds from #55 holes drilled in 1/4" o.d. tubes that lie at both ends of the reeds on the front of the valve box. A pressure of about 110 to 120 psig during flow is required for good starts. An engine will start with equal ease either cold or flooded, with maximum protection against burning of the reeds. Both a standard "short" reed valve box and a "long" reed valve box gave similar good starts in conjunction with AJ-7.5-1 pulsejets of the type used on the XH-26 helicopter.

2. INTRODUCTION

Pulsejets are often started statically with a blast of air from a compressed-air hand line blown into the engine through the air inlet valves. This system provided fairly satisfactory starts on the static stand at the Manhattan Beach plant until the development of a new system of fuel injection was undertaken in which the fuel was introduced upstream of the air inlet valves on the AJ-6.75 "Mugu" pulsejets (L/D ratio of 6.6). These pulsejets were developed as the basic engines for dual ducted packages designed for tests that were planned to be conducted in the Induction Air Blast Facility at the Point Mugu Naval Air Missile Test Center. The investigation of these dual ducted packages was part of the program to develop suitable rotor tip-mounted engines for the MX-1660 four ton cargo helicopter.

Starts on the whirl stands are usually achieved by a procedure called "whirl starting", which consists of bringing the pulsejet up to a tip-speed at which sufficient ram pressure is developed to start the engines. However, it was anticipated that a properly designed ducted pulsejet would slow down the air in the inlet diffuser so much that it would be quite difficult to start without some kind of auxiliary air-start device. Thus it was necessary to develop a reliable remotely controlled start system for such powerplant packages. Furthermore, during testing of the aforementioned system of up-stream fuel injection, there was a serious safety problem when starting the pulsejets with a hand-held air line, due to flash-backs of flame through the air inlet valves. Therefore, development of a new type of integral air-start system was undertaken under the provisions of Item 2.2.2.2 of Exhibit "A" of Contract No. AF 33(600)-15613.

The objective of this starter development program, then, was to develop a quick, positive starting system for pulsejet engines using the NRL type vane-seating air inlet valves, that would provide protection against reed burning during starting, require a minimum amount of starting air and be remotely controlled. By-products of this development have been the application of the new start system to five-inch and 7.5-inch diameter pulsejets and these results have also been reported herein.

3.1 AJ-6.75 Pulsejets With "Upstream" Fuel Injection

In an attempt to improve the performance of the AJ-6.75 "Mugu" pulsejets, a type of fuel system was investigated in which fuel was introduced forward of the air inlet valves. These engines were being started with a hand-held air line, but there was a serious safety problem involved due to flash-backs of flame through the air inlet valves. Remote controls were rigged on the air start tube to reduce the danger to personnel but the nature of the blast of starting air was such that flash-backs continued to damage the air inlet valves. The forward or "upstream" fuel injection system meanwhile evolved from a system that used a fuel nozzle pointed into the air inlet valves to one that consisted of 1/4" o.d. tubes placed at the ends of the valve vanes on both sides of the valve box. A No. 79 hole was drilled in each tube between each set of valves. This provided for 8 jets of fuel from each side of the valve box directed into the combustion chamber through the air inlet valves. The new system reduced the flash-back problem and gave improved engine performance, especially in terms of specific fuel consumption. The next step was to test an air start system similar to the upstream fuel injection system. Air-start tubes (also 1/4" o.d.) were mounted alongside of the fuel tubes as shown in Figure 1, and connected to the plant compressed air system, which provided a maximum of about 120 psig pressure. This "forward" or "upstream" air-tube start system usually gave almost immediate starts and also controlled the flash-back and valve burning problems.

3.2 AJ-6.75 Pulsejets With Internal Baffled-Nozzle Fuel Injection

The new forward air-start system worked so well when used in conjunction with upstream fuel injection that it was then tested on the AJ-6.75 "Mugu" type (L/D = 6.6) pulsejets equipped with the more conventional internal nozzle and baffle fuel system. Practically immediate starts were obtained with this combination, and, in fact, the nozzle and baffle fuel system was perhaps a little easier to start than the upstream fuel system.

3.3 AJ-5.0 Pulsejets With "Upstream" Fuel Injection

Forward air-start tubes were used to start the AJ-5.0 pulsejets on the static test stand when equipped with upstream fuel injection tubes, as shown in Figure 2. The results were quite satisfactory. However, a cowl was required for testing the engine in the air blast in the Wright Air Development Center, Power Plant Laboratory, altitude free-jet test cell. Accordingly, the upstream fuel and air-start tubes were built into a short cowl, as shown in Figure 3. This integral air-start system was somewhat different than the original upstream air-start tube system. Instead of parallel tubes with 6 holes in each of them, as shown in Figure 2 , this system contained four 1/8" o.d., 0.03" wall, bent copper tubes projecting from each side of the valve box in line with fuel spray holes, and one similar tube projecting from each of the other two sides of the valve box. Great difficulty in starting was experienced with this system, so the 1/8" o.d. copper tubing was replaced with 3/16" o.d. 0.03" wall copper tubing. This permitted starts, but they were rather marginal.

A further slight change to the system and a very brief time spent on starting procedure, resulted in a start system and procedure that produced consistent starts within a matter of several seconds. The air-start system change consisted merely in bending the tubes so that they pointed downstream between the valves at an angle of about 15 degrees to the pulsejet axis, and then pinching the tube exits into oval cross-sections, with the long axis of the oval parallel to the axis of the air inlet valves. An advantage of this upstream air-start system over the original system was the reduction of inlet air blockage. Test results indicated that the presence of the air-start tubes, as shown in Figure 2, caused a reduction of peak thrust by as much as 9%.

The successful static starting procedure developed with the combined upstream air and fuel systems (as built into the cowl) was as follows: turn on starting air, fuel, and spark ignition. When fuel flow comes up to about 26 pph, the pulsejet begins weak resonant combustion. After about a ten second warm-up period at this fuel flow, the fuel flow is increased steadily to 35 or 40 pph, where normal resonant combustion occurs. This system did not produce starts nearly as well as the earlier system (without cowl), but it is believed that a modest development period similar to that which produced the earlier system would yield a system that would also produce practically immediate starts.

3.4 AJ-5.0 Pulsejets With Internal Baffled-Nozzle Fuel Injection

The cowl-integral air-start system was constructed after pulsejet M100, with valve box M100, which contained the interior nozzle and baffle, had been shipped to WADC, so no start tests could be made with this fuel system. However, tests with 6.75" and 7.5" diameter pulsejets revealed that the interior fuel nozzle system was even somewhat easier to start with upstream air than was the upstream fuel system. Therefore, no difficulty was anticipated in starting the interior fuel nozzle system with upstream air on the AJ-5.0 pulsejet. Later experience in the WADC Dynamometer 24 free-jet altitude test cell bore out this prediction. This system proved to be easy to start under a variety of altitude and airspeed conditions.

3.5 AJ-7.5-1 Pulsejets With Internal Baffled-Nozzle Fuel Injection

Successful use of the upstream air-start tubes on 5", 6.75", and 7.5" diameter pulsejets led to the application of this system to the AJ-7.5-1 pulsejet powerplants of the XH-26 helicopter. The problem here was to prove out the system within the limitations imposed by the existing helicopter fuel system and air system,or with a minimum of redesign of these existing systems. The following sections describe the specific test and development program that resulted in successful adaptation of this start system to the XH-26 helicopter powerplants. The tests apply specifically to a valve box with standard or "short" reeds with a natural frequency of about 240 cps and a modified AJ-7.5-1 pulsejet, but subsequent testing not specifically described herein, yielded similar results with a "long" reed valve box, with a natural frequency of about 140 cps, on a standard AJ-7.5-1 pulsejet.

3.5.1 Test Equipment

1 - Standard AJ-7.5-1 pulsejet engine, but with a simulated casting support structure which changed the internal shape. Internal air-start ring was not removed but was sealed off externally.

1 - Sharp-lip flight cowl

1 - XH-26 helicopter rotor blade

1 - Fuel, air and ignition lines for rotor blade

1 - Champion V-1 spark plug, .06" gap throughout tests

1 - XH-26 Ship No. 2

1 - each, 20, 25, 30 GPH nozzles

1 - Standard reed valve box

3.5.2 Instrumentation

Fuel Flow - Fisher-Porter "Flowrator" Serial No. 111-1480/2 ± 1% accuracy

Thrust - Hagen Null Balance Thrustorq Meter - last calibration: 4-16-54

Voltage - Simpson Voltmeter, Urodel 240, calibrated 6-12-54

Time - "Galco" stop watch

3.5.3 Procedure and Results

3.5.3.1 Phase I - System Development on Test Stand

Previous work with forward air start tubes used in conjunction with a 7.5" diameter engine on the static stand at Manhattan Beach had established seven No. 55 holes per tube.

The test stand system consisted of two 1/4 x .035 aluminum tubes, each tube drilled with seven No. 55 holes. One tube was on either side of the valve box at the reed ends (Figure 4). The two tubes were held by clips and connected to plant air supply through two 1/4" flexible hoses. Plant air was turned on and off from the test panel by means of an air solenoid valve.

The first variable tested was the angle between the air-jet and the longitudinal axis of the engine. The engine had a 20 gph fuel nozzle and no cowl. See Table 1.

TABLE I

START TIME VERSUS AIR ANGLE

Manifold Air Pressure PSIG	Fuel Flow PPH	Air Angle	Start Time (Seconds)	Augmentor
80	0-200	90°	No start	Yes
80	0-200	90°	No start	No
80	0-200	75°	No start	Yes
80	0-200	75°	No start	No
93	0-140	60°	5	Yes
93	140	60°	7	No
85	140	48° (max)	1	Yes
85	140	48°	2	No

The second variable tested was starting air pressure. 75 psig was found to be a safe minimum pressure for a good start. 75 to 110 psig gave immediate starts; 110 being the maximum attainable from the compressor, as connected.

The effect of starting air pressure was observed, at the best air angle found above (48°), for the 20, 25 and 30 gph fuel nozzles, with and without the augmentor. No cowl was used during this test. Results are shown in Table II.

TABLE II

START TIME VERSUS AIR PRESSURE

	With Augmentor			Without Augmentor		
	Manifold Air Pressure Psig	Fuel Flow PPH	Start Time Seconds	Manifold Air Pressure Psig	Fuel Flow PPH	Start Time Seconds
20 gph Fuel nozzle	35	0-200	No start	33	0-200	No start
	48	100	24	55	100-115	6
	55	115	4	75	140	3
	75-95	120-140	1	95	140	1
25 gph Fuel nozzle	30	0-200	No start	50	0-200	No start
	50	120-140	6	70	120	1
	70	140	1	110	140	2
	90	140	1			
30 gph Fuel nozzle	30	0-200	No start	30	0-200	No start
	50	120-140	3	50	120	4
	70	140	2	70	120	1
	95	140	1	90	120	1

The air pressure versus start time tests were then repeated for all three nozzles, each with and without the augmentor at a simulated helicopter minimum starting fuel pressure of 50 psig. The results are shown in Table III.

The air pressure versus start time tests were then repeated for all three nozzles, each with and without the augmentor at a simulated helicopter minimum starting fuel pressure of 50 psig. The results are shown in Table III.

TABLE III

START TIME VERSUS AIR PRESSURE AT 50 PSIG FUEL PRESSURE

	With Augmentor		Without Augmentor	
	Manifold Air Pressure Psig	Start Time Seconds	Manifold Air Pressure Psig	Start Time Seconds
20 gph Fuel Nozzle	55 80 100	No start 1 1	30 60 105	No start * 5 * 1
25 gph Fuel Nozzle	30 50 70-110	No start 2 1	50 55 68 90 100	No start * 3 * 1 * 1 * 15
30 gph Fuel Nozzle	30 50 70-90	No start 4 1	30 50 70 90-115	No start * 3 * 1 * 2

* Started well but too lean to run.

3.5.3.2 Phase II - System Development on Ship No. 2

At the conclusion of Phase I, a "cowl" model air start system (Figures 5 and 6) was designed and built. The only difference from the Phase I system was that the two tubes lying on either side of the valve box were joined with a "T" which connected to a 1/4" O.D. aluminum supply tube that fitted inside the sharp-lip cowl and ended at the air connection slot in the cowl.

Ship No. 2 was brought to the test stand (Figure 7) and the fuel, air and ignition systems were connected to the engine through a rotor blade supported between the ship and the engine. The blade was used because of its capacitance effect on the ignition system.

The fuel, air and ignition lines running through the blade were flight items. The cowl air system and sharp-lip cowl were installed. A ship battery and coil were installed for ignition. Throughout the succeeding portion of the tests, the battery had a load voltage of 8.0 volts, except where otherwise noted.

The flight systems were now almost exactly duplicated; a slight difference in length of connections and no elevation of the rotor above the ship being the only difference. Both of the above were considered to be inconsequential.

The only change to Ship No. 2 was to increase the free flow air pressure at the engine to 120 psig by adjusting the Grove regulator.

All starts were completely cold except where noted otherwise, i.e., fuel lines were emptied and the engine was cooled with water and air after a start. All starts were immediate, except under Condition D with 2.5 volts load voltage on the battery.

TEST CONDITION A

Ship Air Storage Bottle:	Charged to 1500 psig
Fuel Accumulator:	Charged to 165 psig
Start Technique:	Open throttle, wait until flow meter ball drops, spark and air
Other:	Engine cooled, fuel line drained after start
PURPOSE:	To establish adequacy and reliability of start system
RESULTS:	The above was repeated twice to give three starts, all in about one second, which will hereafter be called an immediate start.

TEST CONDITION B

Air Bottle:	Charged to 1500 psig, not recharged
Fuel Accumulator:	Charged to 165 psig, twice
Start Technique:	Open throttle, wait until flowmeter ball drops, spark and air
Other:	Engine cooled, fuel line drained after start
PURPOSE:	To determine number of starts from air bottle and fuel accumulator
RESULTS:	Three starts were obtained from the accumulator and three more starts were obtained with the remaining air after recharging the accumulator; therefore, the air bottle has twice the accumulator capacity for starting.

TEST CONDITION C

Air Bottle:	Charged to 1500 psig
Fuel Accumulator:	Charged to 165 psig
Start Technique:	Open throttle, wait for 7 seconds, spark and air
Other:	Engine cooled, fuel line drained
PURPOSE:	To unload accumulator for same period of time as required on ship to fill fuel lines (7 seconds); find thrust versus time (Figure 6). Rotor rpm may then be determined to see if sufficient speed would be attained on accumulator fuel to operate fuel pump.
RESULTS:	The above was repeated twice to give three runs at 33, 30 and 30 seconds each.

TEST CONDITION D

Air Bottle:	Charged to 1500 psig
Fuel Accumulator:	Charged to 165 psig
Start Technique:	Open throttle, spark and air immediately
Other:	Engine cooled, lines not drained
PURPOSE:	To determine lowest battery load voltage to give an immediate start
RESULTS:	Three starts were made to 9, 8.25 and 7 volts, one start each. All were immediate starts. Air and fuel recharged. Two more immediate starts were made at 5.5 and 4 volts. The last attempt was at 2.5 volts and was unsatisfactory. No start was achieved.

TEST CONDITION E

Air Bottle:	Charged to 1500 psig
Fuel Accumulators:	Charged to 165 psig (two)
Start Technique:	Open throttle, wait 7 seconds, then spark and air
Other:	Engine was cold, fuel line empty
PURPOSE:	Same as Condition C but with two fuel accumulators
RESULTS:	Engine ran 1.15 minutes. See Figure 6 for thrust versus time

TEST CONDITION F

Air Bottle:	Charged to 1500 psig
Fuel Accumulators:	Charged to 165 psig (two)
Start Technique:	Open throttle, wait 10 seconds, then spark and air
PURPOSE:	To determine start system performance under flooded engine conditions
RESULTS:	Engine started in 1.5 seconds

4. CONCLUSIONS

1. Air jets from No. 55 drill holes in 1/4" O.D. tubing under 120 psig air pressure directed downstream through each set of air inlet valves at an angle of approximately 45° to the engine longitudinal axis provide starts within one or two seconds on pulsejets using NRL type vane-seating air inlet valves.

2. Good starts were achieved with equal ease when the engine was either cold or flooded, with maximum protection against burning of the reeds.

3. The improved air-start system has been used successfully on AJ-5.0, AJ-6.75, and AJ-7.5-1 pulsejets with the baffled-nozzle fuel system, and on AJ-5.0 and AJ-6.75 pulsejets using the new "upstream" fuel system.

4. Both a standard "short" reed valve box and a "long" reed valve box gave similar good starts in conjunction with AJ-7.5-1 pulsejets of the type used on the XH-26 helicopter.

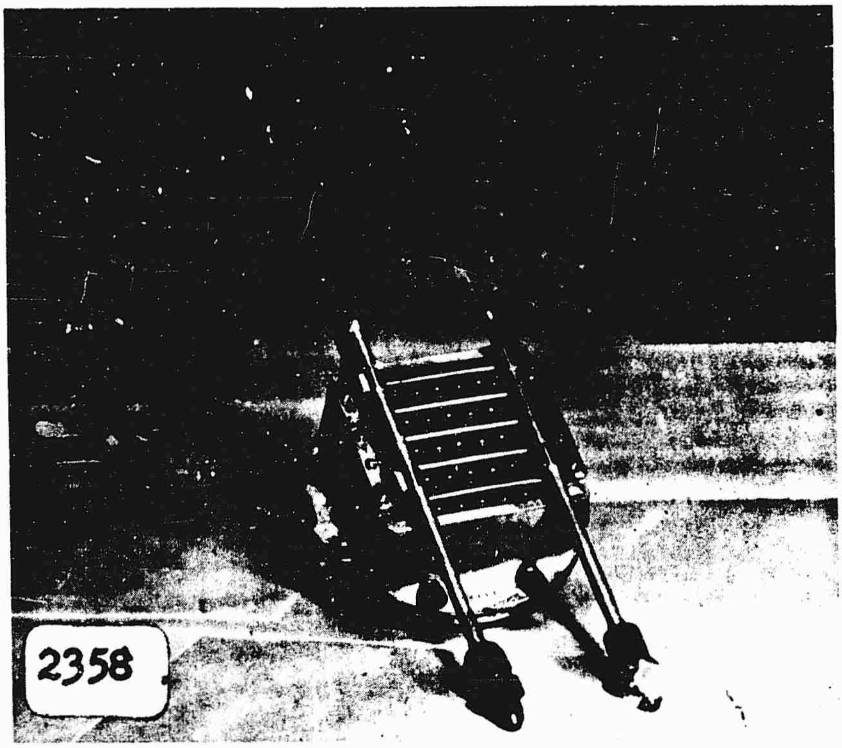

Figure 1 Upstream Fuel and Air-Start Tubes Mounted on AJ-6.75 Pulsejet Valve Box

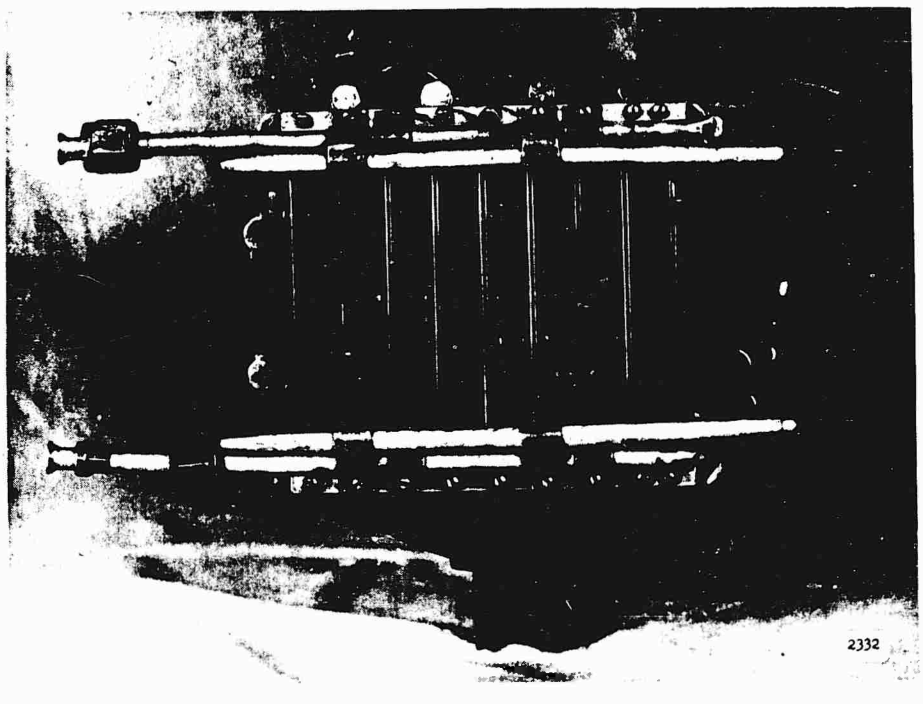

Figure 2 Upstream Fuel and Air-Start Tubes Mounted on AJ-5.0 Pulsejet Valve Box

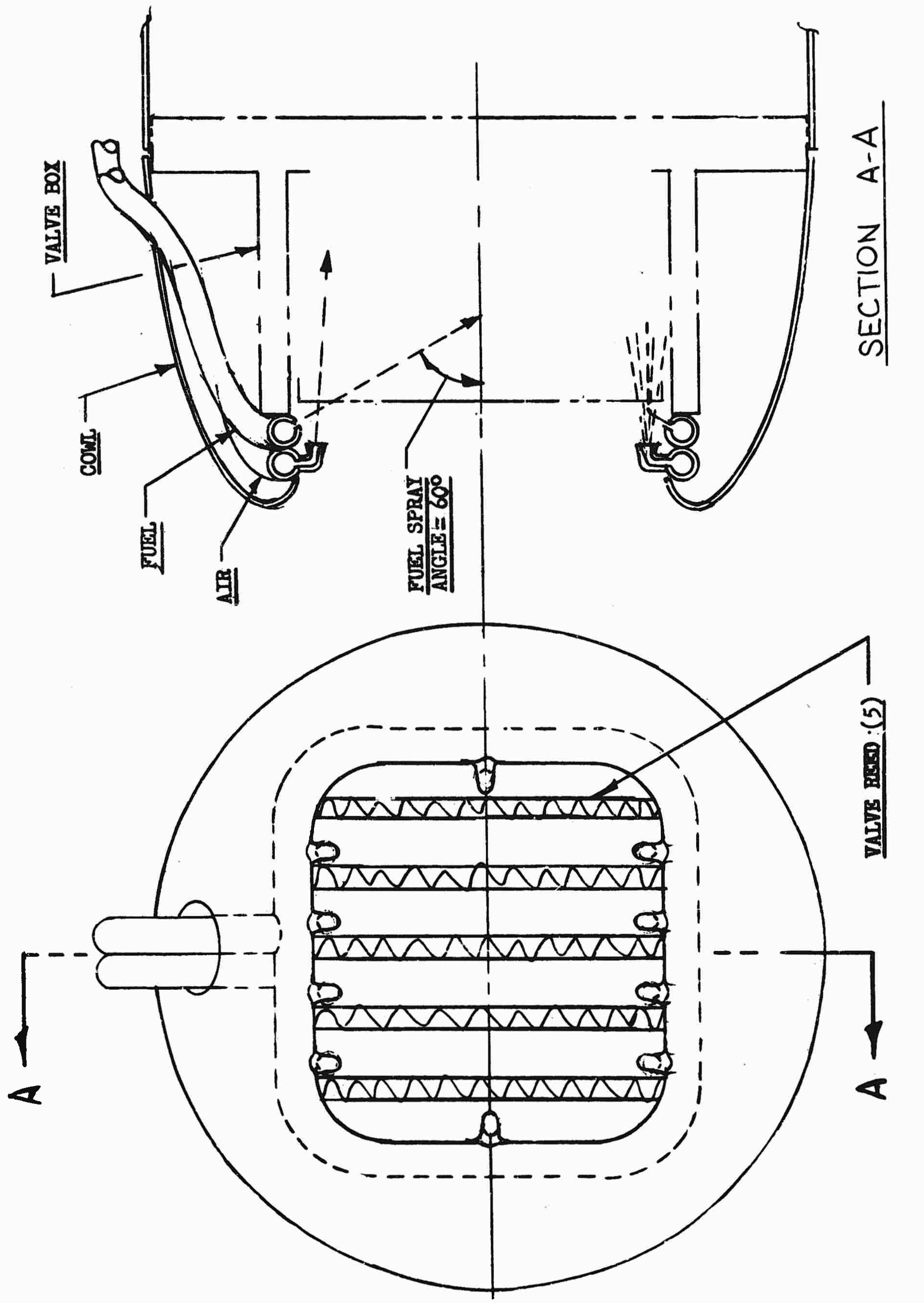

Figure 3 - Cowl for Model AJ-5.0 Pulsejet with Integral Upstream Fuel and Air-Start Systems

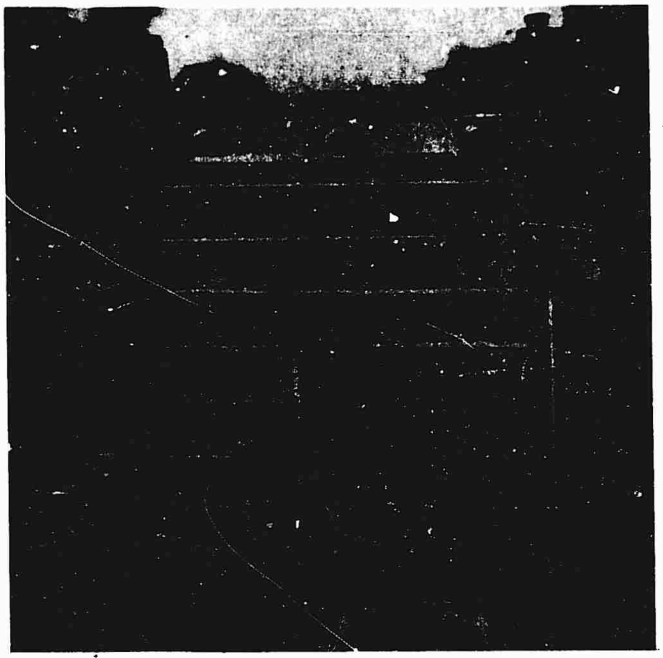

Figure 4 Adjustable-Angle Air-Start Tubes Used on Model AJ-7.5-1 Pulsejet Valve Box

Figure 5 Air-Start Tubes Designed to Fit Inside Pulsejet Inlet Cowl of AJ-7.5-1

Figure 6 Air-Start Tubes Installed Within Cowl of AJ-7.5-1

Figure 7 Test Set-up Showing Connections to the XH-26 Air and Fuel Systems - Including Lines Through the Rotor Blade Seen at the Right